DESIGN OF LONG DISTANCE DISTRIBUTED OPTICAL FIBER SENSOR IN POWER DISTRIBUTION AUTOMATION SYSTEM

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The traditional power distribution automation system monitoring sensors are designed to use dot structure, more difficult to meet the requirements of grid monitoring to measure performance over a long distance, the electromagnetic interference, not suitable for the long-distance network monitoring, in order to improve the management level of distribution automation system, we design a distributed fiber optic sensor for distribution automation system monitoring. The hardware part of the sensor consists of pump laser, coupler, detection module and photodetector. On the basis of analyzing the measurement principle and simulation process of distributed optical fiber sensor, a mathematical model of optical fiber signal modulation based on phase generating carrier technology is established to realize remote monitoring and management of distributed automatic system. The structure of remote distributed optical fiber sensor and the process of distribution automation monitoring system are realized. The effectiveness and reliability of the sensor are verified by simulation experiments. Simulation results show that distributed optical fiber sensor has high monitoring accuracy and stability, and has obvious advantages in optical signal demodulation, sensor capacitance control and integrated monitoring error control.

Keywords: Power distribution system; Long distance; Distributed optical fiber sensor; Phase generation carrier technology (PGC)

1. Introduction

Power distribution automation is the main component of power grid construction and transformation in China, and it is also one of the important links in serving urban and rural power supply and realizing power modernization [1]. Distribution automation system includes distribution management, link scheduling and feeder automation. Distribution automation can realize the monitoring, coordination and remote operation of the whole power supply situation. Communication technology is the core and key of distribution automation [2]. Traditional sensors used in power distribution system communication, such as a sensor based on resistance sampling method designed in reference [3], are used to

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measure neutral DC. This paper analyzed the principle of resistance sampling method and the conditioning circuit of double integral A/D converter, and effectively realized the monitoring of neutral point current in transformer operation. The output characteristic of the sensor was linearly related to temperature, so it was easy to correct it. However, the sensor was susceptible to electromagnetic interference and was not suitable for monitoring long-distance power grids.

Distributed optical fiber sensing technology is based on optical time-domain distribution technology in optical fiber transmission [4]. In the field of sensing measurement and monitoring, distributed optical fiber sensing technology can fully reflect the advantages of optical fiber transmission in distribution and extension. Compared with traditional sensors, optical fiber sensors are compact, easy to carry and install, and easy to match with power distribution automation system. In addition, the optical fiber sensor has good moisture-proof, waterproof and corrosion resistance, and can work in high temperature environment for a long time. As a transmission medium and sensor with optical fiber as signal, optical fiber sensor overcomes the shortcomings of traditional sensors which are vulnerable to electromagnetic interference in the long-distance and distributed monitoring process, and the signal transmission is faster and more accurate [5]. In the sensor measurement of power distribution automation system, the greatest advantage of optical fiber sensor is that it can accurately identify the temperature, stress, damage and other details of the points along the optical fiber without forming a loop, and form a local monitoring network with a considerable scale, which changes the drawbacks of the traditional point-based monitoring network in local missed detection, thus realizing the overall real-time monitoring of whole power system.

In order to improve the management level of power distribution automation system, a distributed optical fiber sensor for monitoring power distribution automation system is designed. The hardware of the sensor consists of coupler, detector, photoelectric detector, laser and other modules. On the basis of explaining the design principle and simulation workflow of the optical fiber sensor, the algorithm based on phase generation carrier technology (PGC) is adopted in the modulation and demodulation of the optical fiber signal, and a mathematical model for the signal processing of the optical fiber sensor is constructed. Finally, the remote monitoring and control of power distribution automation system are realized. The experimental results show that the distributed optical fiber sensor has higher monitoring accuracy and good stability.

2. Methodology

2.1 Design Principle and Hardware Composition of Distributed Optical Fiber Sensor

Distributed optical fiber sensor is based on optical fiber detection technology and adopts distributed structure to manage and monitor the information of power distribution automation system which changes with time and spatial distribution on optical fiber path. The optical fiber sensor demodulates the optical wave signal transmitted through the optical fiber into the modulator of the system, extracts the phase, intensity, frequency and polarization information carried in the signal [6], and obtains the measured parameters and related working information of the power automatic distribution system, so as to realize the monitoring of the working state of the power grid.

When the signal emitted by the light source is injected into the optical fiber, scattering and reflection occur when it propagates in the optical fiber. Some scattered and reflected light in the optical fiber will return to the optical time domain system. The scattering process of the optical signal in the optical fiber is shown in Fig. 1.

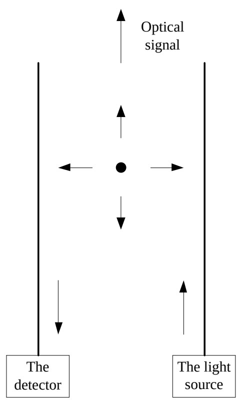

Fig. 1 Diagram of scattering process of optical signal in optical fiber sensor

Assuming that the time difference between the incident light signal and the reflected signal is ξ, the distance d_0 to the reflected point can be calculated by the optical time domain system.

$$d_0 = \frac{\xi \cdot s}{2\eta} \tag{1}$$

Where, η is the effective refractive index of optical fibers and s is the propagation speed of light in vacuum. The basic hardware structure of distributed optical fiber sensor for power distribution automation system based on optical time domain technology and its basic theory is shown in Fig. 2.

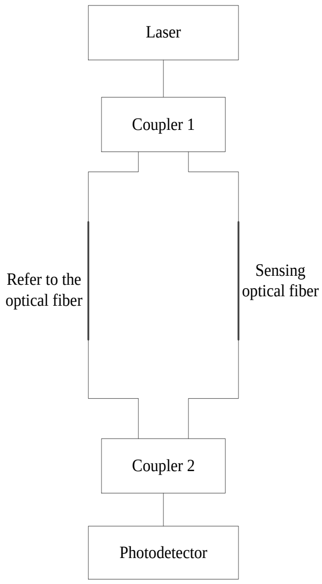

Fig. 2 Hardware architecture of distributed optical fiber sensor

The laser is used as the light source of distributed optical fiber sensor [7]. Rare earth particles are doped in the core of the fiber as the gain medium. The pumping light emitted by the laser source is injected into the fiber. Rare earth ions in the fiber can absorb the pumping light emitted from the laser. Its electrons are stimulated to a higher energy level to realize the inversion of the number of ions [8].

Fiber coupler is used to extend the link of optical fiber and can precisely dock the end face of the optical fiber, couple the light wave signal emitted by the laser into the optical fiber, and minimize the link loss. When the optical fiber coupler increases the opening and closing angle of the branch circuit, there will be light leakage in the cladding, which leads to excess loss. Therefore, the opening and closing angle is generally controlled within 45°. The length of the coupler of the distributed optical fiber sensor should meet the coupling requirements and should not be too short. Before the optical wave signal is transmitted to the photo detector modulation, it must be coupled twice to improve the accuracy of signal demodulation [9].

The optical fiber probe of photoelectric detector is the core functional part of the sensor. The optical fiber cannot exceed its maximum level, otherwise, the phenomenon of light leakage will occur. After the detector receives the scattered light from the phase, the frequency shift v_b of the scattered light can be expressed as:

$$v_b = \varsigma \cdot V \frac{2v_0}{s} \tag{2}$$

Where, v_0 is the frequency of incident light and V is the sound speed in distributed optical fiber sensor. When the stress or temperature in power distribution automation system changes, the sound speed and refractive index of distributed optical fiber core will change simultaneously, which will change the frequency shift of the sensor. The change of stress and temperature in distribution system can be identified by monitoring the frequency shift of distributed sensors. The location of laser scattering points can be accurately measured by controlling the echo time of backscattering light.

The single-mode optical fiber sensor contains two modes of vertical polarization. If external noise or ultrasound interferes with the degenerate state, the phase velocity of the eigen modes in the distributed optical fiber sensor will change, and the mode birefringence will be caused [10]. When the wave length λ is perpendicular to the core, the two sets of strains produced by the light wave in the core can be expressed as follows:

$$\begin{cases} \varepsilon_1 = \left\{ \dfrac{\varepsilon_r - \varepsilon_a}{2} + \dfrac{\left(\varepsilon_r - \varepsilon_a\right)^2}{2} + 4\varepsilon_{ra}^2 \right\} e^{jwt} \\ \varepsilon_2 = \left\{ \dfrac{\varepsilon_r - \varepsilon_a}{2} - \dfrac{\left(\varepsilon_r - \varepsilon_a\right)^2}{2} + 4\varepsilon_{ra}^2 \right\} e^{jwt} \end{cases} \tag{3}$$

Where, ε_r and ε_a are stresses in different directions, w is the angular frequency of light wave, which can be expressed as:

$$w = \frac{2\pi\tau}{\lambda} \tag{4}$$

Since the stresses from all directions will lead to phase changes in both horizontal and vertical directions, let $\Delta\varphi_1$ and $\Delta\varphi_2$ be the phase changes in horizontal and vertical directions respectively, expressed as:

$$\begin{cases} \Delta\varphi_1 = \dfrac{-n_0\left(\zeta_1\varepsilon_1 + \zeta_2\varepsilon_2\right)}{2} \\ \Delta\varphi_2 = \dfrac{-n_0\left(\zeta_2\varepsilon_1 + \zeta_1\varepsilon_2\right)}{2} \end{cases} \tag{5}$$

In the formula, ζ_1 and ζ_2 are photoelastic coefficients in horizontal and vertical directions respectively. Assuming that a laser pulse acts on the probe of distributed optical fiber sensor, the phase and speed of power transmission in distribution automation system will change under the combined action of temperature effect and photoelastic effect. Polarization of incident light oscillates back and forth at the same frequency between elliptically polarized light and linearly polarized light [11]. When the detection sensitivity of distributed optical fiber sensor is in the peak body, the output light intensity W is composed of AC component W_1 and DC component W_2:

$$\begin{cases} W = W_1 + W_2 \\ W = W_0 \left[\frac{1}{2} + n \left| \Delta\varphi_1 \right| \sin wt \right] \end{cases} \tag{6}$$

Where, w is the angular frequency of light wave and W_0 is the intensity of incident light. If the modulation coefficient is very small, the above formula can be simplified as follows:

$$W = W_0 \left[\frac{1}{2} + \left(\Delta\varphi_1 \right) \sin wt \right] \tag{7}$$

Based on the principle of distributed sensor design and the design of optical fiber sensor hardware system, a software algorithm flow for power distribution automation system is proposed according to phase generation carrier technology (PGC).

2.2 Distribution System Monitoring Process based on Distributed Optical Fiber Sensor

The key of monitoring power distribution automation system with distributed optical fiber sensor is to realize demodulation of optical signal [12]. When the signal source emits the signal and inputs the sensing fiber, the optical fiber will undergo slight deformation, and the arm length difference of the sensing fiber relative to the reference fiber will change slightly, which will affect the difference of laser interference intensity. Using photoelectric detector to detect the transmitted light intensity and demodulating the collected optical signal based on PGC demodulation algorithm, the sensing signal containing the internal information of power distribution automation system can be obtained, and the accurate detection of the whole power grid system can be completed. The mathematical model of distributed optical fiber signal modulation based on PGC technology is as follows:

Let I_1 and I_2 be the light intensity of two arms of distributed optical fiber sensor respectively, and $n(t)$ represents the environmental noise of the sensing signal, then the total light intensity output I of the optical fiber sensor is expressed as:

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos\left[c \cos wt + n(t) \right] \tag{8}$$

Let $a = I_1 + I_2$, $b = 2\sqrt{I_1 I_2}$, the above formula (8) be simplified as follows:

$$I = a + b\cos\left[c\cos wt + n(t)\right] \tag{9}$$

Let χ be the ratio of b to a, that is, the visibility of the sensor is:

$$\chi = \frac{b}{a} = \frac{2\sqrt{I_1 I_2}}{I_1 + I_2} \tag{10}$$

The Bessel function is used to redefine the total intensity output I of distributed optical fiber sensor as follows:

$$I = a + a\chi\begin{bmatrix}\cos(c\cos wt)\cos n(t) \\ -\sin(c\cos wt)\sin n(t)\end{bmatrix} \tag{11}$$

Expansion of formula (11) can obtain

$$\cos(c\cos wt) = \tau(c) + 2\sum_{n-1}(-1)^n \cdot \tau(c)\cos 2nwt \tag{12}$$

$$\sin(c\cos wt) = 2\sum_{n-1}(-1)^n \cdot \tau(c)\cos(2n+1)wt \tag{13}$$

Laser interference signal includes AC and DC components, so the product of multiple harmonics of sinusoidal wave and the fundamental frequency of carrier wave should be superimposed. In order to get the sinusoidal wave of the sensing signal, it is necessary to multiply the high-order harmonics with the fundamental frequency of the carrier wave and demodulate it coherently.

Based on the phase generation carrier technology, the signal transmitted from the power distribution automation system can be analyzed and demodulated. The light wave signal is related to the visibility of the sensor, the depth of carrier modulation and the light intensity factor [13]. Therefore, other factors related to the above factors will also have a certain impact on the demodulation results of the signal, such as the split-light ratio of the sensor coupler, the output intensity of the laser, the polarization change of the transmitted light, the intensity attenuation of the transmitted light in the channel, etc. [14-15]. If there is light intensity interference or the output light source is unstable, the demodulation result υ can be expressed as:

$$\upsilon = \chi^2 A^2 (1 + h\cos\omega t)^2 n(t) \tag{14}$$

Where, h is the intensity of interference, A is the average output intensity, ω is the interference frequency of the output intensity. If the sinusoidal wave of the distributed optical fiber sensor is assumed to be $\phi(t)$, the frequency of the initial signal is H_0, and the initial phase difference is ϕ_0, then $\phi(t)$ is:

$$\phi(t) = H_0 \cos \omega t + \phi_0 \tag{15}$$

Finally, the demodulation result of filtering interference can be expressed as:

$$\begin{aligned} \upsilon &= \chi^2 A^2 H_0 \left(1 + h^2 \cos^2 \omega t + 2h \cos \omega t\right) \tau(c) \\ &= \chi^2 A^2 H_0 \tau(c) \left(\frac{1+h^2}{2} \cos \omega t \right) + \frac{h^2 \left[\sin(2\omega) t + \cos(1-2\omega) t \right]}{4} \end{aligned} \tag{16}$$

In summary, a long-distance distributed optical fiber sensor for power distribution automation system is designed. The hardware structure and signal modulation mathematical model of the system are introduced. The phase-generated carrier technology can effectively monitor the performance and stability of power distribution automation system.

3. Results and Discussion

In order to verify the effectiveness of long-distance distributed optical fiber sensor in distribution automation system, this paper compares the method of transformer neutral point DC current sensor based on resistance sampling in reference 3, a method of long-distance radio frequency sensor node with adaptive power management in reference 4 and reference 5. The positioning method based on all-fiber micro-vibration sensor is analyzed by the following simulation experiments. The performance of distributed optical fiber sensor in optical signal demodulation, the performance stability of sensor in extreme environment and the integrated monitoring error control are studied.

Reference 3 A DC sensor for measuring neutral DC is designed based on resistance sampling method. Based on the measuring principle of resistance sampling method and the working principle of the conditioning circuit of double integral A/D converter, an on-line neutral point current monitoring device is installed without power failure of transformer. The output characteristic of the designed DC sensor is linearly related to temperature, which is convenient for on-line calibration of the sensor. When the measuring current is greater than 10A, the measuring error is 2%. When the measuring current is less than 10A, the measuring error is less than 0.2A. The designed DC sensor has been successfully applied to field measurement, and the monitoring data show that it runs reliably. Reference 4 provides a self-sustaining battery-free multi-sensor platform with radio frequency capture capability reduced to 17 dBm and a standard DAsh7 wireless communication interface is implemented. The node runs at the farthest distance of 17 m from 2 W UHF carrier. RF power transmission allows operation when ordinary energy removal sources (such as the sun, heat, etc.) are unavailable, while DAsh7 protocol makes it fully compatible with the standard

Internet of Things infrastructure. An optimized energy acquisition module is designed, including rectenna and integrated nano-power DC/DC converter (mppt). The rectangular antenna is optimized by using the combined design method of non-linearity and electromagnetism to work at ultra-low power level. Ultra-low power microcontrollers control on-board sensors and wireless protocols and adapt power consumption to available detection power by changing the wake-up strategy. The adaptive behavior can be observed on the designed platform, and the data transmission rate is determined dynamically by the RF power. Among the new features of the system, the application of nano-energy acquisition, the realization of hardware/software wake-up strategy, the optimization algorithm of optimum sampling rate, and the adaptive behavior of nodes based on receiving power are mainly introduced. The existence of micro-vibration signal as noise in reference 5 is one of the main factors causing interference and affecting machining accuracy. Precise measurement and location of micro-vibration source is the premise of eliminating interference. To overcome the shortcomings of the existing optical fiber positioning system, a micro-vibration positioning system based on all-optical fiber micro-vibration sensor is proposed. The system needs at least four micro-vibration sensors. By measuring the time difference of arrival (TDOA) of one sensor's vibration signal relative to the other three sensors, the position of micro-vibration source can be calculated.

In order to reduce the interference of external noise and internal noise on signal demodulation effect, the first step is to use band-pass filter to filter the collected light signal in power system and eliminate the out-of-band noise. Fig. 3 and Fig. 4 are the signal amplitude changes before and after demodulation of the distributed optical fiber sensor.

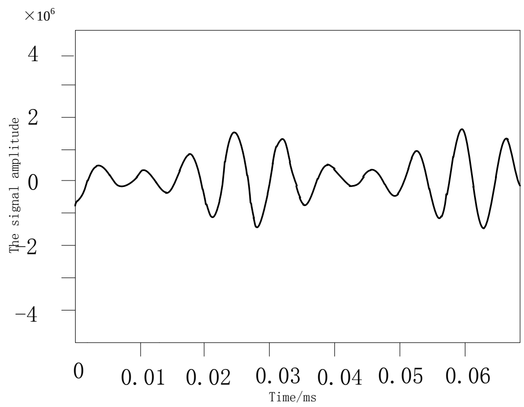

Fig. 3 Signal amplitude before modulation

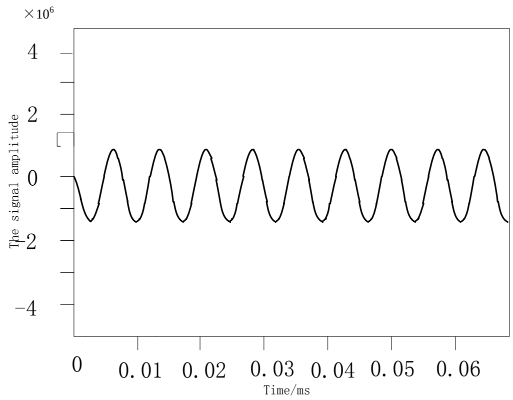

Fig. 4 Signal amplitude modulated by distributed optical fiber sensor

Comprehensive analysis of Fig. 3 and Fig. 4 shows that the fluctuation of signal amplitude before modulation is irregular and the fluctuation curve is confused. The signal amplitude curve modulated by long-distance distributed optical fiber sensor has certain regularity and stable fluctuation period. From the comparison results in the above Fig., it can be concluded that after the demodulation process of the long-distance distributed optical fiber sensor designed in this paper, the interference effect of light intensity has been well suppressed, and good demodulation effect can be obtained.

Because the distributed optical fiber sensor can still maintain good performance under the harsh conditions of high temperature and high humidity, the changes in capacitance of low-voltage arm of the traditional sensor is compared with that of the long-distance distributed optical fiber sensor designed in this paper when the temperature span ($-20℃-80℃$) is large. Let the ambient temperature span be between -30℃ and 40℃. The comparison results are shown in Fig. 5.

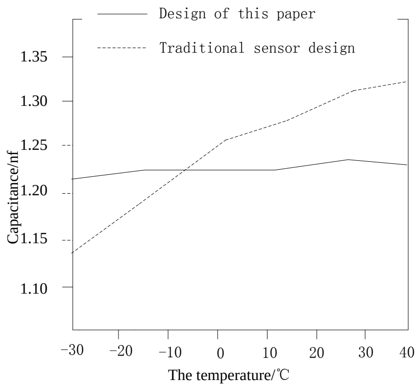

Fig. 5 Changes in capacitance of low-voltage arm

The analysis of Fig. 5 shows that the capacitance of traditional optical fiber sensors varies greatly with temperature when the ambient temperature varies greatly. The range of the capacitance varies from 1.14 to 1.33, while the capacitance of the low-voltage arm of the long-distance optical fiber sensor designed in this paper can be kept between 1.20 and 1.25. This shows that the stability of the long-distance distributed optical fiber sensor is good.

Finally, the traditional sensor and the long-distance distributed optical fiber sensor designed in this paper are extracted to demodulate the light wave signal and control the sensor capacitance value in the monitoring of the power distribution automation system, and the comprehensive errors are counted and compared. The error statistics are shown in Table 1.

Table 1

Comparison of monitoring comprehensive errors

Experimental data	Monitoring comprehensive error%	
	Traditional sensor	Distributed laser sensor
Data set 1	0.851	0.093
Data set 2	0.720	0.095
Data set 3	0.919	0.088
Data set 4	0.654	0.090
Data set 5	0.907	0.079

The analysis table 1 shows that, even if different data sets are input, the monitoring errors of the long-distance distributed optical fiber sensor designed in this paper are less than 0.1% in demodulation of optical signals and capacitance control of sensors, while the integrated monitoring errors of traditional sensors are much larger than those of long-distance distributed optical fiber sensors. The above results show that long-distance distributed optical fiber sensors have high advantages in the monitoring of power distribution automation system.

4. Conclusion

Distribution automation can effectively monitor, coordinate and remotely operate the power supply situation of the whole power grid. Monitoring power distribution automation system can ensure its stability and safety. In view of the fact that traditional sensors are often designed with point structure and are difficult to meet the needs of long-distance monitoring in terms of measurement performance. To this end, this paper designs a long-distance distributed optical fiber sensor for monitoring distribution automation system. In this paper, the construction of long-distance distributed optical fiber sensor and the realization process of monitoring power distribution automation system are introduced, and the validity and reliability of the sensor are proved through simulation experiments.

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R E F E R E N C E S

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